

# CHARACTERIZATION OF FOREST OPACITY USING MULTI-ANGULAR EMISSION AND BACKSCATTER DATA

Mehmet Kurum<sup>(1)</sup>, Peggy E. O'Neill<sup>(1)</sup>, Roger H. Lang<sup>(2)</sup>, Alicia T. Joseph<sup>(1)</sup>,  
Michael H. Cosh<sup>(3)</sup>, and Thomas J. Jackson<sup>(3)</sup>

<sup>(1)</sup> Hydrological Sciences Branch / Code 614.3 NASA Goddard Space Flight Center,  
Greenbelt, MD 20771 USA, [Mehmet.Kurum@nasa.gov](mailto:Mehmet.Kurum@nasa.gov)

<sup>(2)</sup> The George Washington University, Dept. of Elect. & Computer Engineering,  
Washington, DC, 20052 USA

<sup>(3)</sup> Hydrology & Remote Sensing Laboratory, USDA ARS, Beltsville, MD 20705 USA

## ABSTRACT

This paper discusses the results from a series of field experiments using ground-based L-band microwave active/passive sensors. Three independent approaches are employed to the microwave data to determine vegetation opacity of coniferous trees. First, a zero-order radiative transfer model is fitted to multi-angular microwave emissivity data in a least-square sense to provide “effective” vegetation optical depth. Second, a ratio between radar backscatter measurements with the corner reflector under trees and in an open area is calculated to obtain “measured” tree propagation characteristics. Finally, the “theoretical” propagation constant is determined by forward scattering theorem using detailed measurements of size/angle distributions and dielectric constants of the tree constituents (trunk, branches, and needles). The results indicate that “effective” values underestimate attenuation values compared to both “theoretical” and “measured” values.

**Index Terms**— Microwave, radar, radiometer, forest, attenuation.

## 1. INTRODUCTION

Soil moisture is recognized as an important component of the water, energy, and carbon cycles at the interface between the Earth's surface and atmosphere. Several planned microwave space missions, most notably ESA's Soil Moisture Ocean Salinity (SMOS) mission (launched November 2009) and NASA's Soil Moisture Active Passive (SMAP) mission (to be launched 2014/15), are focusing on obtaining accurate soil moisture information over as much of the Earth's land surface as possible [1, 2]. Current baseline retrieval algorithms for SMOS and candidate retrieval algorithms for SMAP are based on the tau-omega model [3], a zero-order radiative transfer approach where

scattering is largely ignored and vegetation canopies are generally treated as a bulk attenuating layer. In this approach, vegetation effects are parameterized by tau and omega, the microwave vegetation opacity and single scattering albedo, respectively. This model has been validated over grasslands, agricultural crops, and generally light to moderate vegetation. Its applicability to areas with a significant tree fraction is unknown, especially with respect to specific tree types, anisotropic canopy structure, and presence of leaves and/or understory.

Although not really suitable to forests, Ferrazzoli *et al.* [4] proposed that a zero-order tau-omega model might be applied to such vegetation canopies with large scatterers, but that equivalent or effective parameters would have to be used. They determined these effective parameters by minimizing a cost function computed from the difference between measured multi-angular dual-polarized emissivity and modeled data (tau-omega model).

This paper compares the effective vegetation parameters computed from multi-angular pine tree microwave emissivity data with the results of two independent approaches which provide “theoretical” and “measured” vegetation characteristics. These two techniques are based on forward scattering theory [5] and radar corner reflector measurements [6], respectively. The results demonstrate that “effective” vegetation optical depths are lower than “theoretical” and “measured” ones.

## 2. ACTIVE/PASSIVE MICROWAVE EXPERIMENTS OVER PINE TREES

During 2008 and 2009, active/passive dual-polarized microwave measurements were acquired over a natural stand of Virginia pine coniferous trees at multiple incidence angles (from 15° to 55° with 10° increment) [7]. The supporting ground truth data were also collected.



(a)



(b)

Figure 1 Pictures of the trihedral taken from (a) front and (b) behind during the radar measurements.

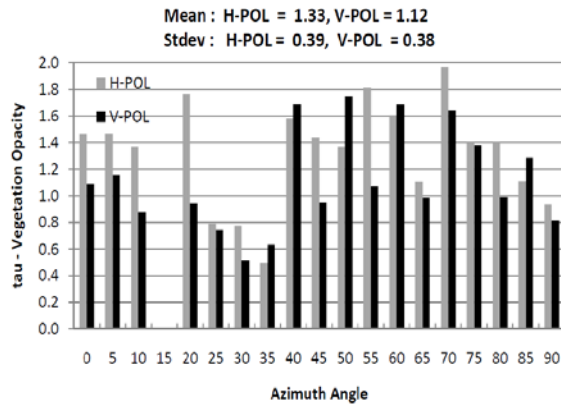


Figure 2 “Measured” vegetation optical thicknesses from trihedral experiment at incidence angle of 45° on September 15, 2009.

The soils of the pine tree site were loamy sand, with textures varying from 57% sand, 13.6% clay to 87% sand, 3.4% clay depending on location within the site. Tree heights average about 12 m, with DBH (diameter at breast height) varying from 4 to 29 cm. Surface roughness was very small, with an *rms* roughness height < 0.5 cm. The forest floor had a surface layer of loose debris/needles and an organic transition layer above the soil.

In addition to the regular active/passive data, a separate radar experiment with and without trihedral corner reflector (with 1.22 m front edge length) under trees was carried out in September 15, 2009 as shown in Fig. 1. The goal of this experiment was to measure forest opacity directly by radar as an independent estimate. The data were collected at a 45° incidence angle and at 19 different azimuth locations (from 0° to 90° with 5° increment) to get an average estimate.

The L-band microwave instrument system used in this study is called ComRAD for Combined Radar/Radiometer. The system is mounted on a 19-m hydraulic boom truck and has been developed jointly by NASA/GSFC and George Washington University. It includes a dual-pol 1.4 GHz radiometer and a quad-pol 1.25 GHz FMCW radar sharing the same 1.22-m parabolic dish antenna with a 12° field of view.

### 3. TECHNIQUES TO DETERMINE FOREST OPACITY

In this section, the forest optical depths are calculated by three independent techniques. Summary of these techniques are given below:

#### 3.1. Trihedral Corner Reflector Approach– “Measured”

Trihedral corner reflectors are widely used for external radar calibration since they yield large backscattering radar cross sections over wide azimuth and elevation angular ranges [6]. This approach is based on the expected strong return from a corner reflector under trees. It assumes that coupling between the corner reflector and the surrounding background and trees is small. Basically, the ratio between co-polarized radar backscatter measurements with the corner reflector under trees and in an open area provides the loss in propagation through trees. This retrieved forest opacity represents the “measured” opacity  $\tau_m$ , which is given by:

$$\tau_m = -\frac{\cos \theta}{2} \ln \frac{\sigma_{m2}^0 - \sigma_{m1}^0}{\sigma_{m4}^0 - \sigma_{m3}^0} \quad (1.a)$$

where

$$\sigma_{m1}^0 = \sigma_d^0 + \sigma_{dr}^0 \quad (1.b)$$

$$\sigma_{m2}^0 = \sigma_d^0 + \sigma_{dr}^0 + e^{-2\tau_m \sec \theta} \sigma_{cr}^0 \quad (1.c)$$

$$\sigma_{m3}^0 = \sigma_{bckgrd}^0 \quad (1.d)$$

$$\sigma_{m4}^0 = \sigma_{cr}^0 + \sigma_{bckgrd}^0 \quad (1.e)$$

The quantity  $\sigma_{m1}^0$  is measured backscattering coefficient from trees and it is composed of volume ( $\sigma_d^0$ ) and double interaction terms ( $\sigma_{dr}^0$ ) [5]. The backscattering coefficient of the measurement with trihedral under tree is denoted by  $\sigma_{m2}^0$  and it includes a return from the corner reflector ( $\sigma_{cr}^0$ ) attenuated by the vegetation volume ( $e^{-2\tau_m \sec \theta}$ ). Radar measurement of background in an open field is represented by  $\sigma_{m3}^0$  and measurement of trihedral in an open area is denoted by  $\sigma_{m4}^0$ .

Fig. 2 shows the “measured” vegetation opacity values obtained at angle of incidence  $45^\circ$  using the radar returns with and without trihedral corner reflector under trees at several azimuth locations. The “measured” vegetation optical depth at h-polarized channel is  $1.33 \pm 0.39$  while “measured” v-polarized one is  $1.12 \pm 0.38$ .

### 3.2. Multi-Angular Emissivity Approach – “Effective”

The principle of this approach depends on exploiting multi-angular emissivity data in order to retrieve simultaneously geophysical products such as soil moisture and vegetation characteristics [8]. The algorithm uses an iterative approach, minimizing a cost function computed from the differences between measured and modeled brightness temperature data, for all available incidence angles. It provides “effective” or equivalent vegetation parameters [4]. Recently, this approach was also tested by using L-band microwave measurements over a coniferous (pine) and deciduous forest [9].

The values of effective vegetation optical depth  $\tau_{eff}$  and single scattering albedo  $\omega_{eff}$  are calculated by minimizing the following merit function:

$$\min \sqrt{\sum_{i=1}^N \sum_{p=h,v} [e_p^{(0)}(\tau_{eff}, \omega_{eff}, \theta_i) - e_{mp}(\theta_i)]^2} \quad (2)$$

where  $\tau_{eff}$  and  $\omega_{eff}$  act as free parameters and are defined as independent of polarization and angle,  $\theta_i$  is the observation angle from the nadir,  $e_{mp}$  is measured  $p$ -polarized emissivity, and  $e_p^{(0)}$  is modeled  $p$ -polarized zero-order radiative transfer emissivity (tau-omega model [3]). The subscript  $p$  denotes polarization and it can be horizontal (h) or vertical (v). In this minimization, it is assumed that surface reflectivities are known *a priori*. In this investigation, they are calculated by using a three-layer soil forest floor model that includes a litter layer (loose debris/needles), a transition layer (organic humus), and soil [7].

In Fig. 3, the measured microwave emissivity collected on September 8, 2008 is plotted over the observation angles from  $15^\circ$  to  $55^\circ$  along with the results of the fitted zero-order tau-omega model to compare the model with data. Fig. 4

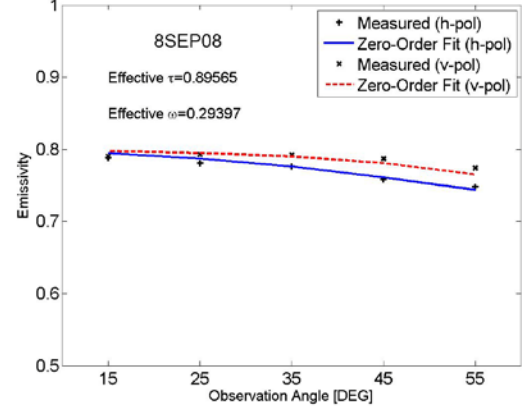


Figure 3 Radiometer angular response from Virginia pine forest and the fitted zero order model for data collected on September 08, 2008.

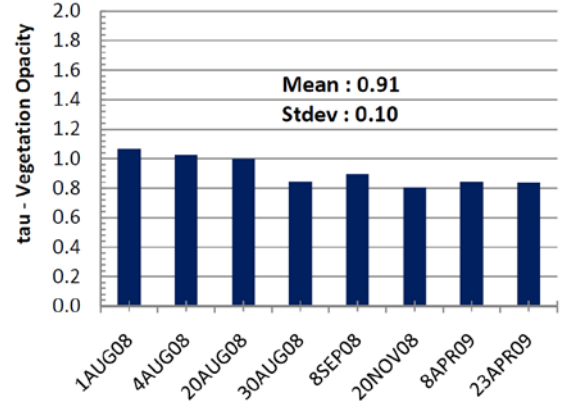


Figure 4 “Effective” vegetation optical thicknesses from the multi-angular emissivity data.

demonstrates “effective” opacities computed at different days over almost a year span (from August 1, 2008 to April 23, 2009). The “effective” vegetation optical depth for all measurements is found to be  $0.91 \pm 0.10$ .

### 3.3. Forward Scattering Approach – “Theoretical”

The vegetation propagation constant is determined by the forward scattering amplitudes of each of the tree constituents, averaged over all particle sizes and angle orientations [5]. Since the forward scattering amplitude of an arbitrary particle is a complex quantity, then this medium will attenuate the wave. This technique requires detailed measurements of size/angle distributions and dielectric constants of the tree constituents (trunk, branches, and needles). These data were obtained by destructive tree sampling. The calculated forest parameters in this technique represent “theoretical” values.

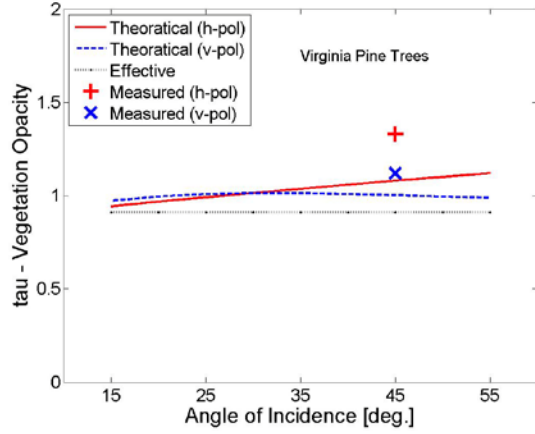


Figure 5 Vegetation optical thicknesses comparison.

The vegetation opacity or optical thickness is given by  $\tau_p(\theta) = \kappa_{ep}(\theta)d$ , where  $\theta$  is the observation angle from the nadir,  $d$  is thickness of the vegetation layer, and the volume extinction coefficient is defined by:

$$\kappa_{ep}(\theta) = \frac{4\pi}{k_0} \sum_{\alpha} \rho_{\alpha} \Im \{ \langle f_{pp}^{(\alpha)} \rangle \} \quad p \in \{h, v\} \quad (3)$$

where the angular brackets denote ensemble average over the angular and size statistics of particles, the number density of the scatterer type  $\alpha$  is given by  $\rho_{\alpha}$ , and  $k_0$  is the wave number,  $k_0 = 2\pi f_0/c$ , where  $f_0$  is the frequency and  $c$  is the speed of light in free space. Notice that in this formula  $f_{pp}^{(\alpha)}$  is the forward scattering amplitude of the  $\alpha^{th}$  type of scatterers and the scatterer type  $\alpha$  can be branch, leaf/needle, or trunk. The subscript  $p$  denotes polarization.

In Fig. 5, angular and polarization dependences of “theoretical” vegetation optical depth are plotted. The figure also includes “measured” h- and v-polarized vegetation opacity at 45° and “effective” opacity for comparison purposes. As seen from the plots, the followings can be concluded: (a) “effective” values are lower than both “measured” and “theoretical” values; (b) “theoretical” opacity depends weakly on angle and polarization. This result provides a basis to choose effective values as independent of polarization and angle in (2); (c) “measured” opacities are higher than the other results and are more polarization dependent than the “theoretical” result at incidence angle of 45°.

#### 4. CONCLUSION

In this paper, vegetation opacity was characterized by three independent approaches based on multi-angular pine tree microwave emissivity data (“effective” opacity), radar corner reflector measurements (“measured” opacity), and

forward scattering theory (“theoretical” opacity). The results from these techniques are compared and they demonstrate that “effective” values are lower than both “measured” and “theoretical” values.

#### 5. REFERENCES

- [1] Y. H. Kerr, P. Waldteufel, J. P. Wigneron, S. Delwart, F. Cabot, J. Boutin, M. J. Escorihuela, J. Font, N. Reul, C. Gruhier, S. E. Juglea, M. R. Drinkwater, A. Hahne, M. Martin-Neira, and S. Mecklenburg, “The SMOS Mission: New Tool for Monitoring Key Elements of the Global Water Cycle,” *Proceedings of the IEEE*, vol. 98, no. 5, pp. 666 - 687, May 2010.
- [2] D. Entekhabi, E. Njoku, P. E. O’Neill, K. Kellogg, W. Crow, W. Edelstein, J. Entin, S. Goodman, T. Jackson, J. Johnson, J. Kimball, J. Piepmeier, R. Koster, N. Martin, K. McDonald, M. Moghaddam, S. Moran, R. Reichle, J.C. Shi, M. Spencer, S. Thrman, L. Tsang, and V. Jakob, “The Soil Moisture Active and Passive (SMAP) Mission,” *Proceedings of the IEEE*, vol. 98, no. 5, pp. 704 - 716, May 2010.
- [3] T. Mo, B. Choudhury, T. Schmugge, J. Wang, and T. A. Jackson, “Model for microwave emission from vegetation covered fields”, *Journal of Geophysical Research*, vol. 87, no. C13, pp. 11229-11238, 1982.
- [4] P. Ferrazzoli, L. Guerriero, and J. P. Wigneron “Simulating L-band emission of forests in view of future satellite applications,” *IEEE Transaction on Geosciences and Remote Sensing*, vol. 40, pp. 2700-2708, December 2002.
- [5] N. S. Chauhan, R. H. Lang, and K. J. Ranson, “Radar modeling of a boreal forest”, *IEEE Transaction on Geosciences and Remote Sensing*, vol. 29, pp. 627-638, 1991
- [6] F. T. Ulaby (Editor, Preface), C. Elachi (Preface), *Radar Polarimetry for Geoscience Applications*, Artech House Publishers, ch. 5, 1990.
- [7] M. Kurum, P. E. O’Neill, R. H. Lang, C. Utku, A. T. Joseph, M. H. Cosh, T. J. Jackson, “Passive Measurements over Conifer Forest at L-Band: Modeling of the Forest Floor”, presented, *IEEE Microrad*, Washington, DC (USA), March 1 – 4, 2010.
- [8] J. P. Wigneron , Y. H. Kerr , P. Waldteufel , K. Saleh , M.-J. Escorihuela , P. Richaume , P. Ferrazzoli , P. de Rosnay , R. Gurney , J. C. Calvet , J. P. Grant , M. Guglielmetti , B. Hornbuckle , C. Matzler , T. Pellarin and M. Schwank, “L-band microwave emission of the biosphere (L-MEB) model: Description and calibration against experimental data sets over crop fields,” *Remote Sensing of Environment*, vol. 107, pp. 639-655, April 2007.
- [9] J. P. Grant, K. Saleh-Contell, J. P. Wigneron, M. Guglielmetti, Y. H. Kerr, M. Schwank, N. Skou, A. A. Van de Griend, “Calibration of the L-MEB model over a coniferous and a deciduous forest”, *IEEE Transaction on Geosciences and Remote Sensing*, vol. 46, no. 3, pp. 808-818, March 2008.